A NOVEL DISC-TYPE RELUCTANCE MOTOR

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Abstract This paper explores the theory and potential of a family of reluctance motors as well as brief review of different types of reluctance motors, motivated by the increased demands for geometric versatility and ruggedness for electric motors. This paper presents a new and novel disc type reluctance motor that has been designed built, tested, and analyzed. The magnetic circuit-based analysis shows an obtainable torque per volume 5 KNm/m^3 for the motor which is comparable with other types of electric motors.

Key Words Reluctance Motors, Electric Motors, Electric Machines, Disc-Type Motors, Disc-Type Reluctance Motors

چکیده افزایش تقاضا برای تطبیق پذیری شکل هندسی موتورهای الکتریکی با فضای کاربرد و حفظ مشخصه های عملیاتی، انگیزهٔ تحقیقات را دراین زمینه بوجود آورده است، موتورهای رلوکتانس با مشخصه های کاربردی خوبی که دارا هستند از قبیل گشتاور بالا، داشتن سرعت زیاد و سهولت در ساخت، از جمله موتورهایی میباشند که دراین راستا مدنظر قرار گرفته اند. این مقاله، به معرفی یک نوع موتور رلوکتانس جدید از نوع دیسکی که طراحی، ساخت آزمایش و آنالیز شده خواهد پرداخت. همچنین تحلیل مشخصه های عملیاتی موتور رلوکتانس ارائه شده است. این تحلیل شامل یک مطالعه روی مدار معادل مغناطیسی موتور به علاوهٔ اندازه گیریهای آزمایشگاهی می باشد. در آنالیز مدار مغناطیسی معادل موتور، یک گشتاور بر واحد حجم حدود ۵$KN.m/m^3$، برای این موتور رلوکتانس میتوان بدست آورد که قابل مقایسه با انواع دیگر موتورهای الکتریکی می باشند.

INTRODUCTION

This paper presents a new class of reluctance motors. As a result of several years of research, a well developed technology in the area of reluctance motors and converter drives has now evolved. A reluctance motor consists of a rotor which has no windings of any kind and is free to rotate between the pole pieces of a stationary singly or multiply excited magnetic structure known as the stator. Torque is produced by the tendency of the rotor to align itself with the stator magnetic field. This type of motor offers a number of advantages including [1, 5] simplicity in construction and cooling, geometric versatility, durability, and higher permissible rotor temperature. The types of reluctance motors available in the marketplace today are primarily of the regular cylindrical geometry although the disc geometries have been proposed in limited use. This paper proposes and demonstrates a new disc-type reluctance motor. Athough the origin of the term "switched reluctance" is not clear, one of the earliest occurrences is in relation to a rudimentary disc motor employing switched dc, as noted by Miller [1]. Lawrenson was perhaps the first to adopt the term "switched reluctance" in relation to radial-airgap motor [2], which is the focus of attention today. The term "brushless reluctance-motor" [3], "variable reluctance motor" [4], and "commutated reluctance-motor [1], are among several equally acceptable alternatives used today. In variable speed and high speed applications the advantages of reluctance motors clearly supersede their disadvantages. Hence, they are worthy of investigation.

1. TYPES OF RELUCTANCE MOTORS

There are two types of reluctance motors: regular, doubly-salient, cylindrical motors and disc-type motors. This classification stems from the general shape of the motor.

1.1 Regular Doubly-Salient Cylindrical Motors

This type of motor has salient poles on both stator and rotor (i.e., it is a doubly-salient), as shown in Figure 1. The angles β_r and β_s are rotor and stator arcs, respectively. The windings on the stator are concentrated coils. There are no windings of any kind on the rotor. The current in the stator circuits are switched on and off in accordance with the rotor position.

The torque is developed by the tendency of the magnetic circuit to adopt a configuration of minimum reluctance. This corresponds to the rotor aligning with the stator poles and maximizing the inductance of the excited coils. As discussed in [2], this simple form of current control creates torque-speed characteristics typical of series connected dc-machines.

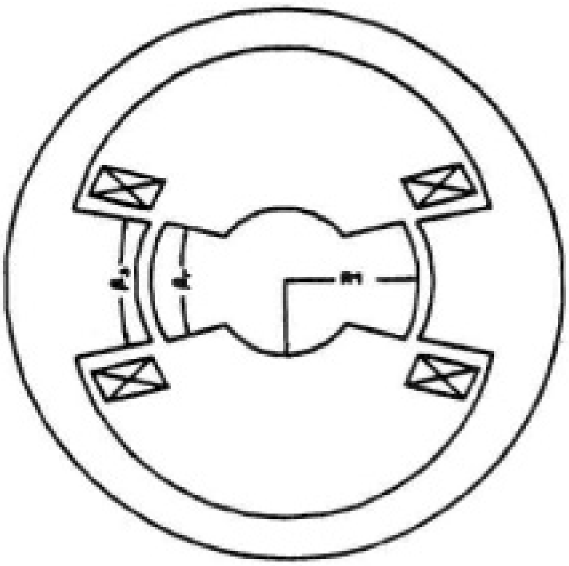


Figure 1. Elements of Doubly-salient Reluctance Motor.

1.2 Disc-Type Reluctance Motor

Direct current motors with disc rotors are widely used. Disc rotors have been proposed for reluctance motors as well [1]. The need for a disctype reluctance motor arises in applications where the spacing is of the primary concern. This geometry is of particular interest in this paper since the paper proposes a different arrangement and positioning of the rotor and the stator in motors of this type. The term "disc-motor" is derived from the geometry of the rotor and the first such motors were demonstrated in [6-11]. The resulting physical shape of the motor can vary from a small diameter and relatively a long length at one extreme, to a large diameter and short length, (i.e., pancake-shape) at the other extreme, with many variations in between. Therefore, this type of motor has a great flexibility of size and shape, the motor can be designed to match the unusual space requirements of many applications. A general simplified version of the disc-type reluctance motor configuration (Figure 2) showning the presence of a thick rotor inside of the stator poles for the purpose of producing higher torque.

The constructional simplicity of the motor is obvious. The primary contribution of the present

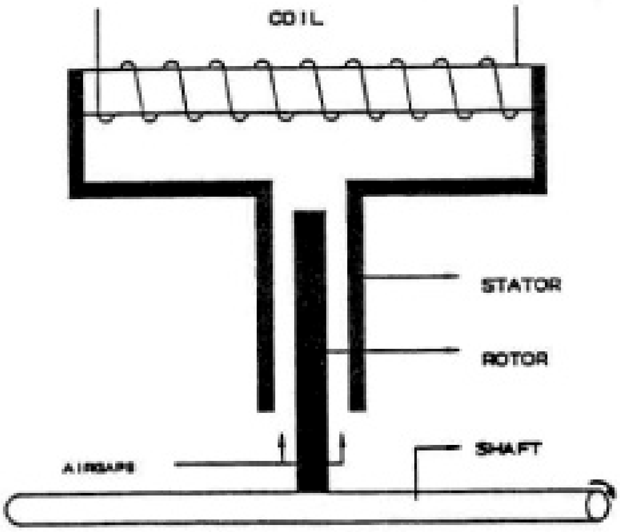


Figure 2. Disc-Type Reluctance motor (align)

paper is to introduce a new disc-type reluctance motor that is even simpler.

2. NOVEL DISC-TYPE RELUCTANCE MOTOR

This section presents a new class of reluctance motors. The novel feature of this motor is a change in the position of the rotors with respect to the stator (i.e., the rotors are positioned outside a set of axially aligned solenoidal stator coils). To fully understand the characteristics of this motor, one can perform magnetic circuit-based, numerical, and experimental analyses. These procedures result in obtaining values for the torque and the maximum and minimum inductances. The result of these analyses can be used to optimize the motor design.

2.1 Double Rotor Disc-Type Reluctance Motor

The production of the torque in the regular disc-type reluctance motor requires a sufficiently thick rotor relative to the airgap as mentioned previously in Section 1.2. In order to reduce the thickness of the rotor, resulting in a more versatile geometry, low inertia, as well as achieving a higher torque, this study considers the usage of a different configuration for the rotor and stator positions. The new disc geometry is fundamentally different from the traditional disc-type reluctance motor. In the new geometry, the rotors are positioned outside the stator, rather than the conventional method of positioning the rotor inside, relative to the stator as discussed earlier in Section 1,2. Figure 3 shows the new disc-type reluctance motor. The two rotors are connected by a shaft running through the middle of the motor. These rotors have the same shape and size. They are positioned in such a way that the rotor blades face each other.

It is apparent that the maximum inductance (corresponding to the minimum reluctance) is achieved when the rotor poles are aligned with the stator poles, meaning the airgap length is the smallest possible and the area of overlap between the rotor and stator is at its maximum. On the other hand, the minimum inductance corresponding to maximum reluctance is obtained when the rotor poles are not aligned with the stator poles, meaning the airgap length is the largest possible and the overlap area between the rotor and stator poles is at its minimum.

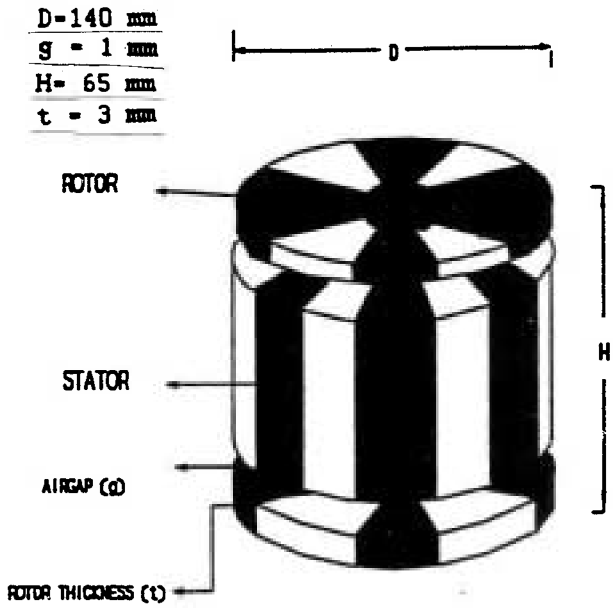
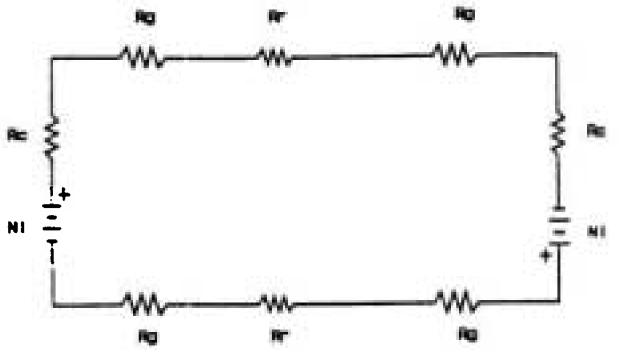


Figure 3. Double rotor disc-type reluctance motor

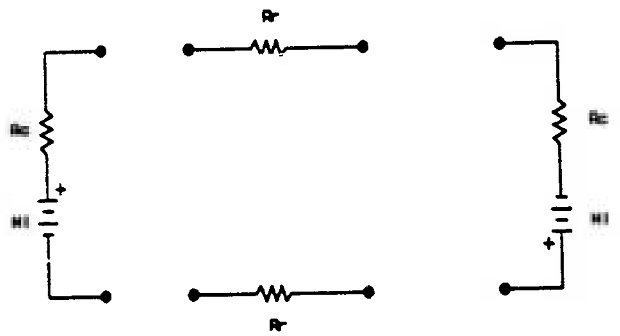
2.2 Linear Magnetic Circuit-Based Analysis

In order to estimate the maximum and minimum inductances, the torque produced by the motor, and the magnetic field, B, in the stator core for low current level with negligible fringing effect, the equivalent magnetic circuits for the motor can be constructed. Each segment of the rotor, stator, and each part of the airgap are presented by its equivalent reluctance. In addition, the coils are modled as voltage sources. The results are equivalent circuits for aligned and non-aligned stator and rotor poles as shown in Figure 4 (a and b, respectively).

The overlap area, A, between the rotor and the corresponding stator for some angle θ, where



a)



b)

Figure 4. a) An equivalent circuit for aligned case b) An equivalent circuit for non-aligned case

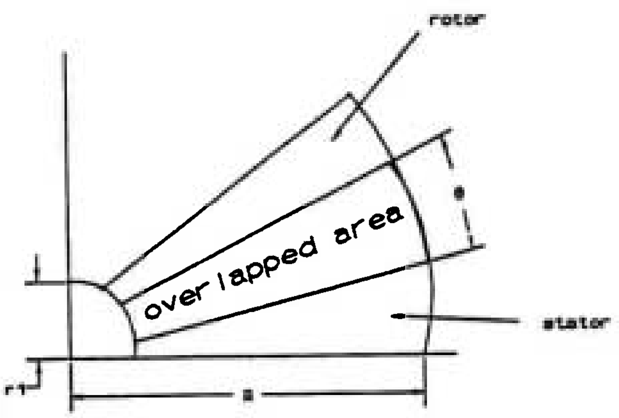


Figure 5. Overlap area between a rotor and a stator

$0<\theta<\pi/6$ is shown in Figure 5.

This overlap area can be calculated by

$$A=\frac{(R-r_1)^2}{2}\times\theta \tag{1}$$

where R is the outer radius of the stator, and r_1 is the inner radius of the stator pole

The total airgap reluctance for the overlap area is

$$\mathcal{R}_s=\frac{g}{\mu_0 A}=\frac{2g}{\mu_0 (R-r_1)^2\,\theta} \tag{2}$$

where g is the length of the airgap. μ_0 is the permeability of air, and θ is the angle of the overlap area.

Therefore, the reluctance of the motor which consists of four airgaps in series is

$$\mathcal{R}_{gm}=\frac{8g}{\mu_0 (R-r_1)^2\,\theta} \tag{3}$$

The total reluctance of the motor including the rotor and cores can be written as

$$\mathcal{R}_t=\mathcal{R}_c+\mathcal{R}_{gm} \tag{4}$$

Where $\mathcal{R}_c$ is the reluctance of stator cores plus the rotors and can be written as

$$\mathcal{R}_c=\frac{l_r}{\mu A_r}+\frac{l_s}{\mu A_s} \tag{5}$$

where l_r and l_s are rotor and stator lengths, and A_r and A_s are rotor and stator areas respectively

Hence, the corresponding inductance is

$$L=\frac{N^2}{\mathcal{R}_t} \tag{6}$$

In which N is the total number of turns.

Finally, the torque can be calculated for this linear circuit by

$$T=\frac{1}{2}\left(\frac{\Delta L}{\Delta\theta}\right)i^2=\frac{1}{2}\left(\frac{L_{max}-L_{min}}{\theta_{max}-\theta_{min}}\right)i^2 \tag{7}$$

Where:

L_{max} is the inductance for aligned case,

L_{min} is the inductance for non-aligned case,

θ_{max} is the maximum rotor deflection from aligned position,

θ_{min} is the minimum rotor deflection from aligned position, and i is the current through the motor coils.

It should be noted that from Figure 4b, the reluctance of the circuit approaches infinity; hence, the resulting inductance approaches zero. The torque per unit volume can be found by dividing Equation 7 by the motor volume

$$T_V = \frac{T}{V} = \frac{(L_{max} L_{min})\, i^2}{2\pi r^2 h\,(\theta_{max} - \theta_{min})} \quad (8)$$

Where h is the height of the motor, and
r is the radius of the motor;

Therefore, the torque per unit volume for the double rotor disc-type reluctance motor is

$$T_V = \frac{N^2 i^2}{2\pi r^2 h\,(\theta_{max} - \theta_{min})} \quad (9)$$

The maximum inductance is calculated using Equation is

$$L = \frac{N^2}{\ } = \frac{N^2}{\frac{X}{\mu_0 A_g} + \frac{l}{\mu_c A}} \quad (10)$$

The minimum inductance is zero, since the fringing effect is not considered. Further there is no overlap area between the stator and the rotor. Figure 6 shows the torque produced by the motor for different current magnitudes using Equation 7.

2.3 Experimental Study

The purpose of this section is to determine the motor parameters in order to predict some of the basic characteristics of the double rotor disc-type reluctance motor. These parameters are the determination of the material property used in the construction of the motor such as, the B-H curve, the minimum and maximum inductance variations for different current magnitudes, and finally, the static torque produced by the motor. In order to determine the properties of the material (i.e., permeability, B-H curve, Figure 7) used in the construction of the motor, several tests have been performed and the following B-H curve been obtained.

The maximum and minimum inductance variations for the reluctance motor are found by using the slip test concept [12]. In this test a constant voltage

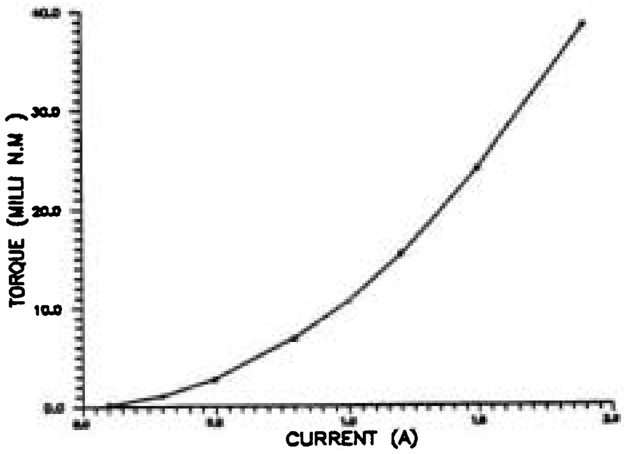


Figure 6. Torque versus current

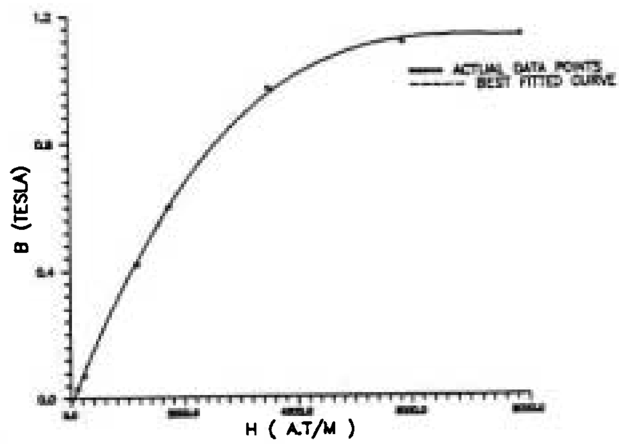


Figure 7. B-H curve for the motor material

magnitude is applied to the proper windings of the motor and the current is monitored on the oscilloscope as the motor rotates. Since the inductance varies with rotor position while applied voltage is constant, the current magnitude will vary with the rotor position. The maximum inductance is found when the current magnitude is at its lowest value, while the minumum inductance is achieved when the current magnitude is at its highest value. The maximum and minimum inductances measured for different current magnitudes; (by measuring the voltage across the motor and the current through the phase windings) are shown in Figure 8 (a & b).

The static torque values of the motor for different current magnitudes are measured using a low range torque meter connected to the shaft of the motor.

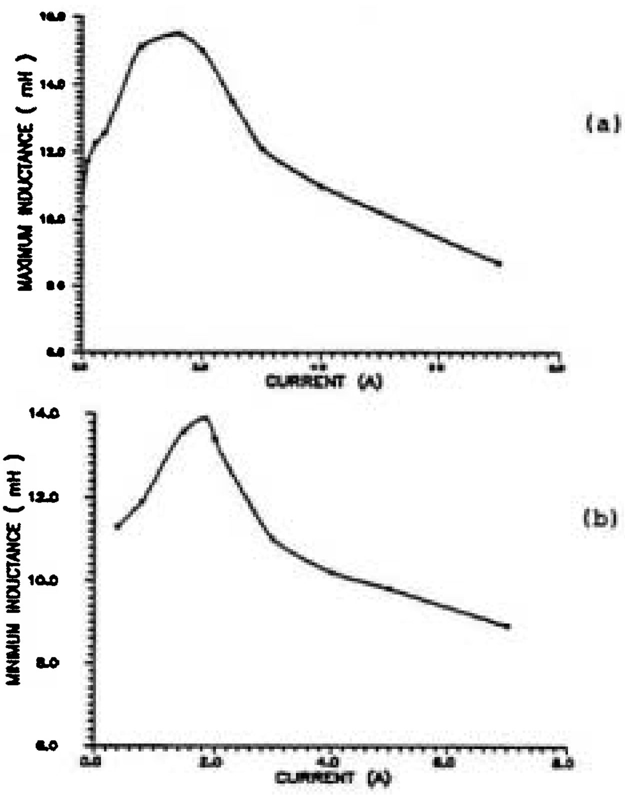


Figure 8. a) Maximum inductance for aligned case
b) Minimum inductance for non-aligned case

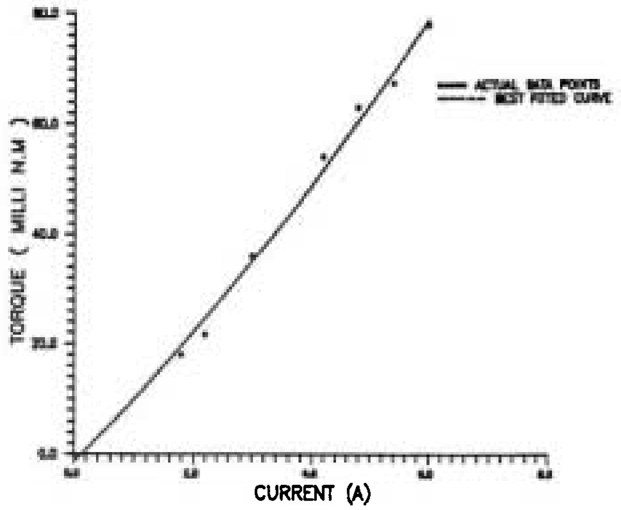


Figure 9. Static torque vs current magnitude

Figure 9 shows a plot of the static torque versus the current magnitude.

CONCLUSION

In conclusion, the overall results obtained for experimental and calculated values of the inductance magnetic field density, and static following manner. The value for the maximum inductance calculated based on the magnetic circuit analysis is 11 mH, which is within the range of the plot of the maximum inductance (Figure 8). It should be noted that, the difference between the inductance values obtained by these two methods stem from the assumption made in the analysis of the magnetic circuit. These assumptions did not include the flux leakages and mutual inductances. Furthermore, in the magnetic base circuit analysis, the magnetic field was assumed to be uniform throughout the core material. The magnitude of magnetic field density in the stator core obtained experimentally is within 10% of the calculated values obtained by the magnetic circuit based analysis. When comparing the static torque measurment obtained experimentally with the calculated torque obtained from magnetic circuit base analysis (3.4), a 5% difference in the low range current levels (I<1 Å) and a 45% difference in higher range $(1<I<2)$ are observed. The higher calculated torque values for the magnetic circuit based analysis are due to the assumptions made for the magnetic circuit based analysis in which the fringing is neglected. Important results for the reluctance motor performance can be obtained by extrapolating several motor parameters. These parameters include higher value for the relative permeability with smaller airgap lengths and higher number of turns. It can be observed that with a relative permeability of 3600, 400 turns per each stator pole, and an airgap length of .2 mm applied to Equations 6 for the maximum inductance and 9 for the torque-per-volume computation of such size and shape, the motor will produce about .657 H and 2.5 $KN.m/m^3$ with a current of 2 Å, respectively. If the motor does not saturate for a current of 4 Å a torque per volume of 10 $KN.m/m^3$ can be obtained using Equation 9. Interpolation between these values (torque per unit volume) suggests that a torque per unit volume of 5 $KN.m/m^3$ is achievable. Hence, this motor shows a great comparability with other types of reluctance motors.

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